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SEED BANKS FOR MAGNETIC FLUX COMPRESSION GENERATORS

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SEED BANKS FOR MAGNETIC FLUX COMPRESSION GENERATORS

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I. INTRODUCTION

In recent years the Lawrence Livermore National Laboratory (LLNL) has been conducting experiments that require pulsed high currents to be delivered into inductive loads. The loads fall into two categories 1) pulsed high field magnets and 2) the input stage of Magnetic Flux Compression Generators (MFCG). Three capacitor banks of increasing energy storage and controls sophistication have been designed and constructed to drive these loads. One bank was developed for the magnet driving application (20kV ≈30kJ maximum stored energy.) Two banks where constructed as MFCG seed banks (12kV ≈43kJ and 26kV ≈450kJ). This paper will describe the design of each bank including switching, controls, circuit protection and safety.

II. MAGNET DRIVER BANK

In early 2005 the magnet driving bank was designed to support a laboratory experiment"to study the effect of magnetic fields on electron thermal transport in laser plasmas" [1]. The original base requirement was to be able to drive a 144μH magnet to ≈15kA.

A prototype capacitor bank that had been used as part of the development for the National Ignition Facility (NIF) laser was available as surplus. This bank consisted of three (3) 48μF/35kV capacitors, a spark gap output switch and the associated energy dissipation (dump) resistors and Ross HV relay. The bank was enclosed in a 183cm (6ft) tall by 152cm (5ft) wide by 61cm (24inch) deep Hoffman enclosure on wheels.

For ease of operation and future growth the spark gap switch was replaced with a size "D" ignitron (National Electronics NL-8900). The ignitron was triggered by a standard LLNL SCR trigger chassis and trigger transformer developed in the late 1970's as part of the Shiva/Nova laser programs. The anode was heated with a simple resistive block heater, 6.3VAC power to the heater was provided by a 50kVDC HV isolation transformer (Stangenes Ind. SI-3271). The cathode was cooled using facility low conductivity water.

A new integrated (in the same enclosure as the bank) control system was designed that allowed for both local and remote control of charging of the bank. The control system was very simplified using only relay logic for interlocks and controls. Charging voltage is supplied by a 20kV 300W Glassman FX20P-15 HV power supply limiting stored energy to ≈30kJ.

Important design features (see Figure 1) are the resistors R1-3 in series with the capacitors and the switches S1 and S2. The resistors (HVR High Energy Disk resistors) perform three functions 1) they provide a "soft" crowbar (resistance limits peak current/flash) when the knife switches are placed in the "safe" position 2) they limit fault current if one of the capacitors should fail and the remaining capacitors attempted to discharge into the failed unit and 3) They provide damping to reduce voltage reversal on the capacitors. S1 and S2 are LLNL internally designed manually operated large high voltage knife switches. The switches are operated by the use of an insulated "grounding stick". The switches have two positions 1) the capacitor and resistor are selected and are part of the high voltage circuit or 2) the capacitor is deselected, may not be charged and any residual charge is dissipated by the series resistor. Note also that with just two switches any combination of one, two or three capacitors can be selected.

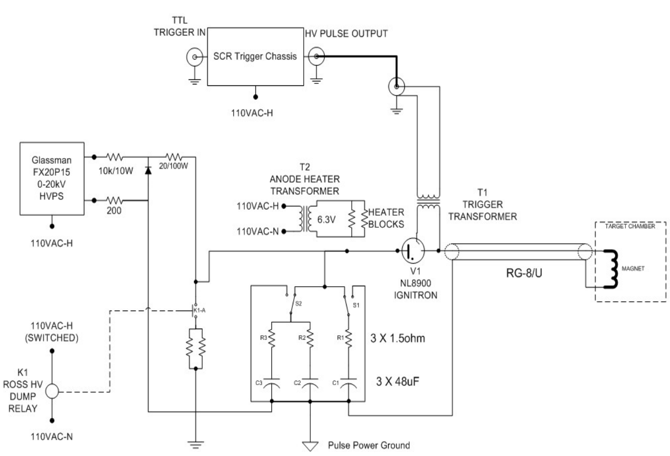

Figure 1 Magnet Pulser High Voltage Circuit

Over the life of the experiment new magnets were designed reducing the inductance of the load and increasing the current desired by the experimenter. In 2006 the inductance of the coil dropped to 15µH (at 25kA). This reduction in inductance resulted in a circuit that was considerably under damped requiring the addition of a diode stack (3 ea. ABB 27Z1350) across the pulser output to reduce ringing. In 2008 the inductance was further reduced to 1µH and peak current increased 88kA [2]. The 2008 changes required the reduction of the series resistors from 1.5Ω to 0.25Ω and addition of two more diode stacks to handle the increase in output current.

The output cable was a single RG-8/U ≈10M (≈30Ft) in length. In 2008 due to the increased output current and reduced inductance of the load a second parallel RG-8/U cable was added.

III. MFCG SEED BANKS

A. 10kA Seed Bank

The first unit designed to seed a MFCG was very similar to the magnet bank with a single 290µF/24kV capacitor in place of the three 48µF units. The baseline requirement was 10kA into a 300µH load with no more than a +12kV charging voltage. The 12kV limitation was to protect the particular load. A second 290µF capacitor was installed in the enclosure (but never connected) to allow for the possibility of driving two MFCG loads simultaneously. Maximum stored energy (2 290µF capacitors @ 12kV) was ≈43kJ.

The bank was enclosed in a 183cm (6ft) tall by 183cm (6ft) wide by 61cm (24inch) deep wheeled Hoffman enclosure .Again a size "D" ignitron was used as the main switch. The ignitron was triggered by a commercial NorthStar IG5F2 Ignitron Driver. Cathode cooling is provided by an external chiller unit (NESLAB) with a built in deionization unit.

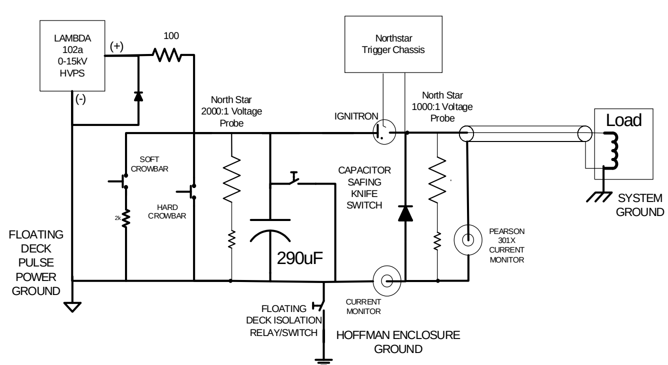

Figure 2 10kA Seed Bank

An unusual requirement for a high energy capacitor bank was that the entire seed bank had to be isolated from ground at shot time. The only connection to experiment's single point ground was via the shields of the output cables. The voltage standoff requirement was +20kV from "Pulse Power Ground" to "Green Wire Ground". For safety reasons the two ground systems are kept tied together via a HV relay. In operation the isolation relay is only opened after the capacitor bank is charged and closed immediately after the shot. To maintain an accurate voltage on the energy storage capacitor(s) the HV power supply continues to operate through shot time. 120VAC Power for the power supply and its controls when the bank is isolated was provided by a battery powered uninterruptible power supply (UPS).

Like the magnet bank the control system was integrated into the bank enclosure. The new control was however much more complex requiring computer control. This led to EMI problems resulting in a decision to remotely locate future control systems and make all control connections to the seed bank via fiber optics.

Output cables where 3 parallel 16m (≈50ft) lengths of Belden YK-198 high votage cable. The output connector was constructed to handle up to six (6) cables.

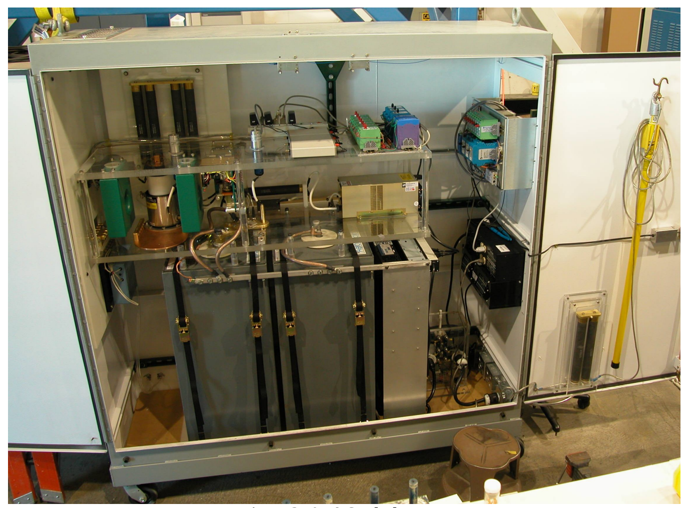

Figure 3 10KA Seed Photo

The output current pulse into an operating MFCG is shown in Figure 4. The positive "blip" at the peak of the current waveform is caused by a shorting of the output cables caused by the explosive operation of the MFCG.

The bank was used to seed a three stage MCFG system. For an input current of 8.5kA the input stage developed approximately 800kA out. The final output of the complete system was over 60MA.

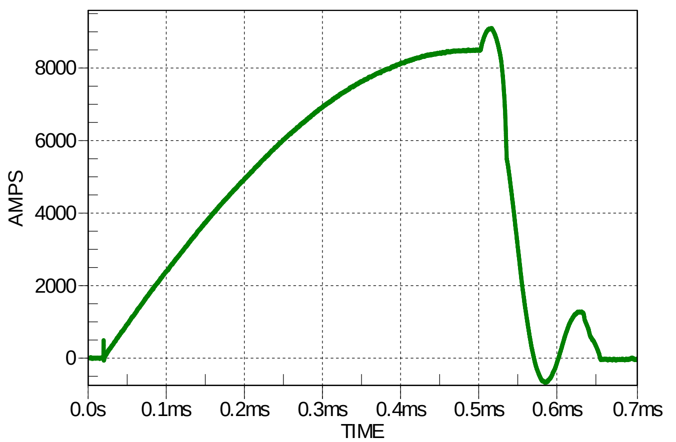

Figure 4 10kA Seed Bank Output Current

B. 150kA Seed Bank

The most recent bank is a 26kV 1300µF unit capable of seeding over 150kA into a nominal load inductance of ≈30µH. The basic topography of this bank is very similar to the previous units but the energy storage is a factor of 10 to 15 times greater in only about twice the volume. The bank consists of two sub modules, the Switch/Output Module and the Capacitor Bank Module. The modules may be separated for construction or maintenance but operated joined together as shown in Figure 5. Overall the assembly is 295cm (9' 8") by 183cm (6ft) tall by 76cm (30 inches) deep and weighs ≈2400kg (5200 lbs).

Figure 5 150kA Seed Bank in Test Cell

Four 330µF/26kV General Atomics Energy Product capacitors provide energy storage. The capacitors are based on units originally developed for NIF. At full voltage the bank stores ≈450KJ. Each capacitor has a 9.1µF inductor in series with its output bushing to limit peak currents in case of a fault. These inductors are identical to ones used in the NIF power conditioning system. A partial list of faults analyzed included; 1) A capacitor failure resulting in the discharge of the remaining capacitors into the failed unit 2) a failure at the load or 3) the failure of an output connector. In all cases the peak fault currents were less than the rated fault current of the capacitors (119kA).

The output ignitron and triggering were identical to the 10kA seed bank. The output switch was grossly over sized for the original lower current application, but was on hand and simplified development of that bank. The NL-8900 ignitron is rated for 300kA making it an excellent fit to the current requirement

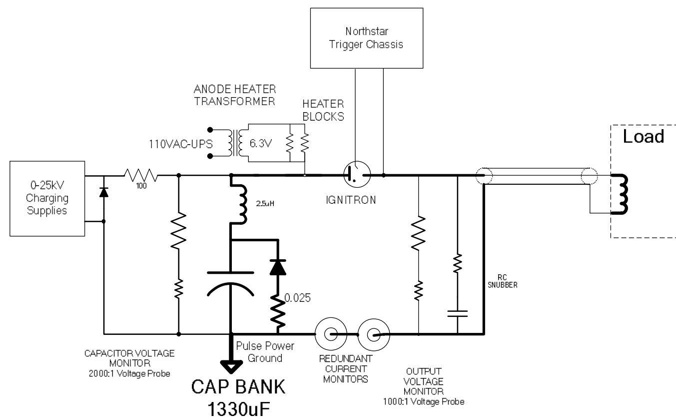

Figure 6 150kA Seed Bank Circuit

The main energy storage capacitors are charged in a two step process. Initially two power supplies are operated in parallel to provide ≈9kJ/s charging the bank in about 1 minute. When the bank is fully charged the 8kJ/s unit is shut down and isolated from the floating deck (See Figure 7). The 1kJ/s supply continues to operate through shot time assuring an accurate bank voltage. AC power to the floating deck is provided 50kVDC isolation transformers (replacing the UPS unit used in the 10kA bank).

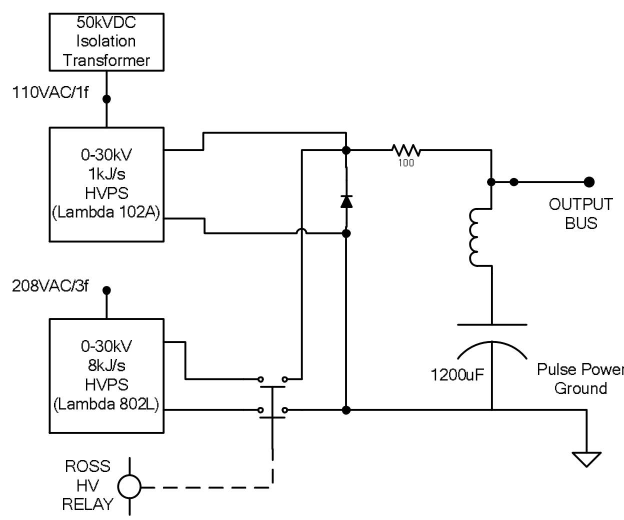

Figure 7 150kA Seed Bank Charging System

For safety purposes a system of automatic and manual "crowbar switches" are employed (Figure 8). Each capacitor has its own manual knife switch that actuated using a grounded safety pole. A pair of redundant Ross HV relays switch in a ladder network of eight resistors. Each bank of four resistors can absorb the entire energy of the bank. In order for this system to fail both relays and all four resistors in a single bank must fail.

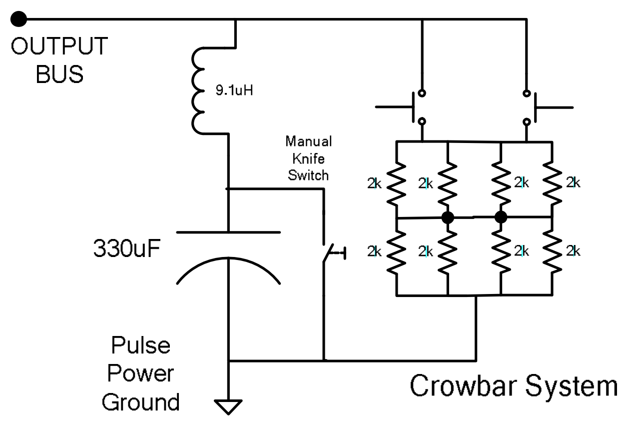

Figure 8 150kA Seed Bank Crowbar System

The voltage isolation requirement for pulse power ground was initially increased +40kV (compared to the +20kV requirement of the 10kA Seed Bank) and recently upgraded to ±50kV.

The control System was located in the control bunker. A PLC unit communicated with the Seed Bank modules through a system of Weed Instruments Co. industrial fiber optic control links. These included analog and digital signals as well as mechanical switch modules. The Human Machine Interface (HMI) was done using LabView© software running on a remote PC via a fiber optic Ethernet network.

The bank was connected to the MFCG using 4 parallel 25m (80 ft.) lengths of Dielectric Sciences DS-2248 HV coaxial cable. The Seed Bank output is configured to allow up to eight output cables.

The output current waveform is shown in Figure 9. Note that the bank was not operating at full output. Only 100kA of seed was desired on this particular experiment. The DC charge voltage in this case was only ≈18kV.

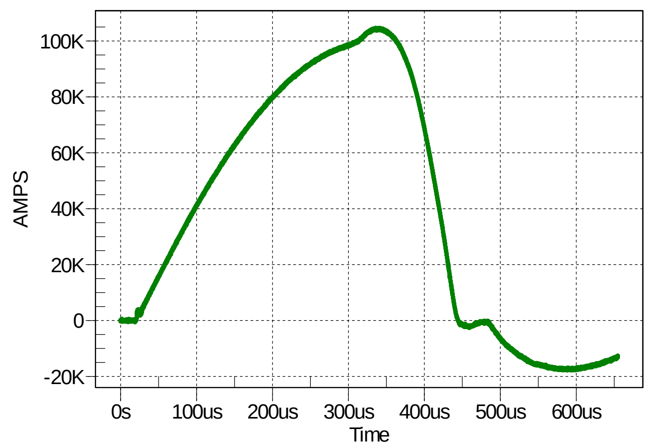

Figure 9 150kA Seed Bank Output Current

For a 100kA seed current the first stage of the MFCG delivered an approximately 17MA output pulse. The entire two stage system output current was approximately 100MA.

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